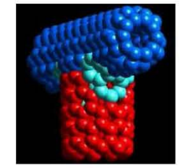
Nanomaterials for Electronics and Optoelectronics



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Outline

NACNT

- Brief introduction to nanomaterials
- Electronics applications
- Memory devices
- Optoelectronics

Various Inorganic Nanowires

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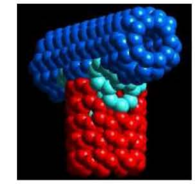
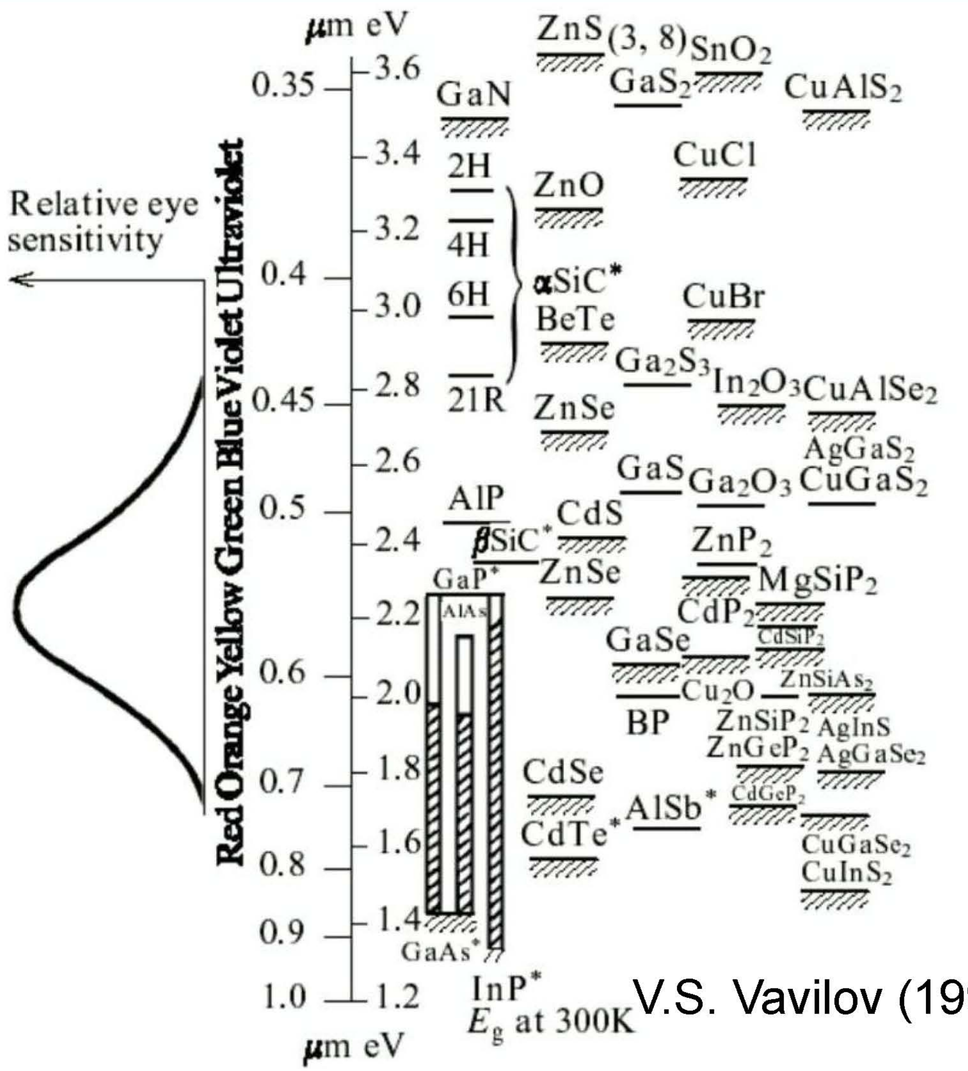




V.S. Vavilov (1994)

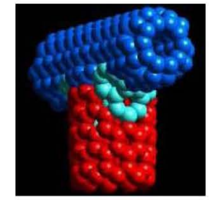
Down to 0.4 eV

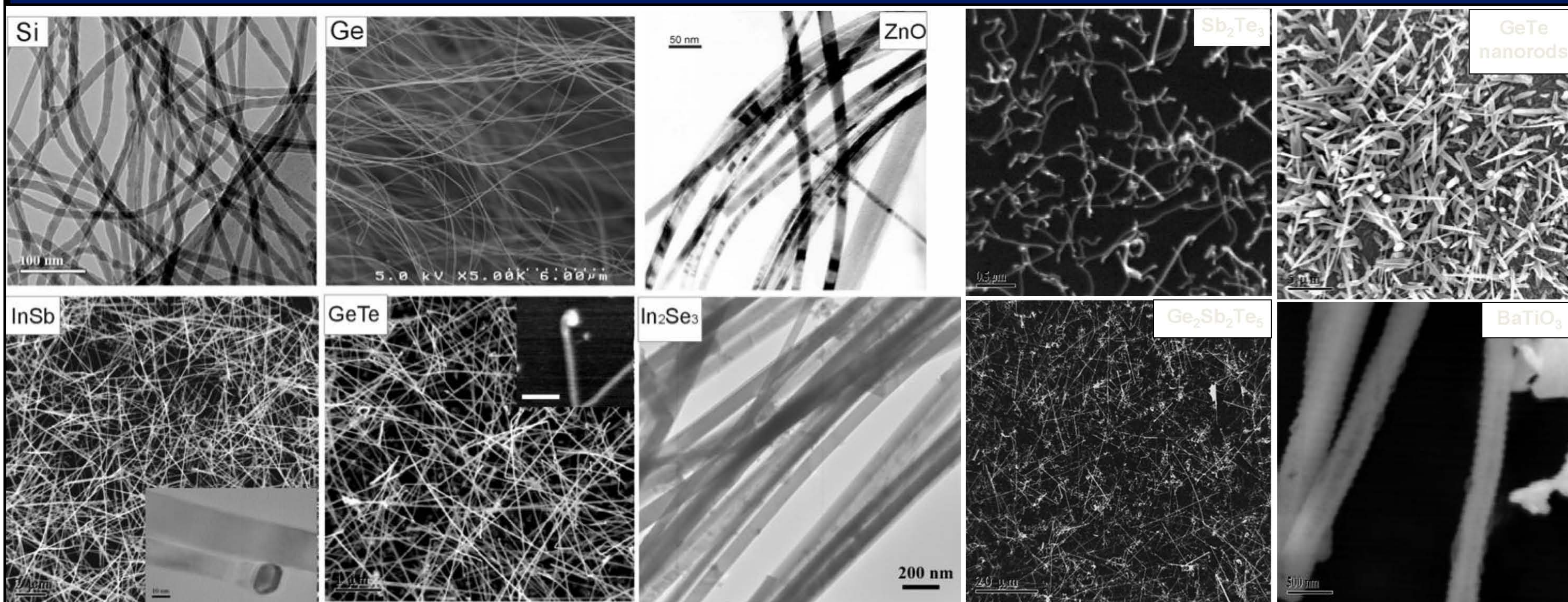
- All these have been grown as 2-d thin films in the last three decades
- Current focus is to grow 1-d nanowires

Motivation

- One-dimensional quantum confinement
- Bandgap varies with wire diameter
- Single crystal with well-defined surface structural properties
- Tunable electronic properties by doping
- Truly bottom-up integration possible

Inorganic Nanowires synthesized at NASA Ames





- Growth by VLS technique
- Si, Ge, nitrides (GaN, AlN, InN), Oxides (ZnO, In_2O_3, SnO, ITO, GaO), GaSb, InSb, CdTe, $BaTiO_3$, PCMs (GeTe, GeSbTe, GeSb, In_2Se_3…)

Vertically-Aligned Nanowires for Device Fabrication

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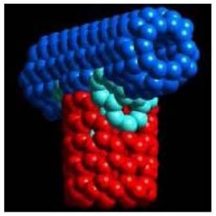
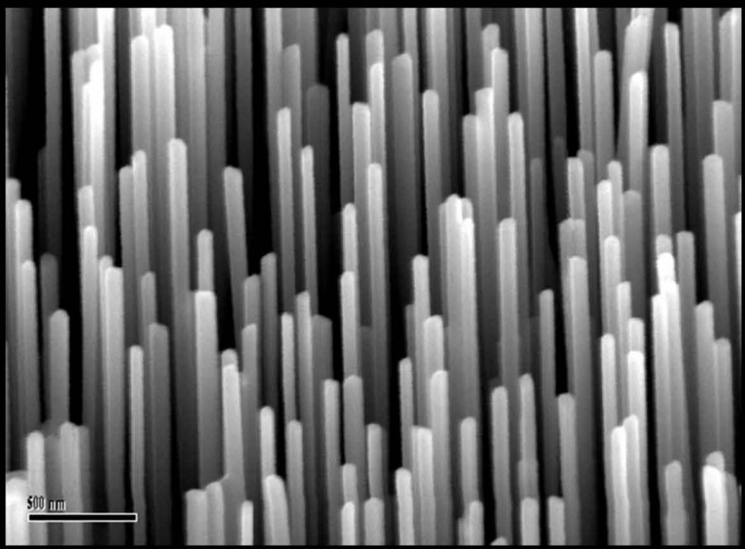
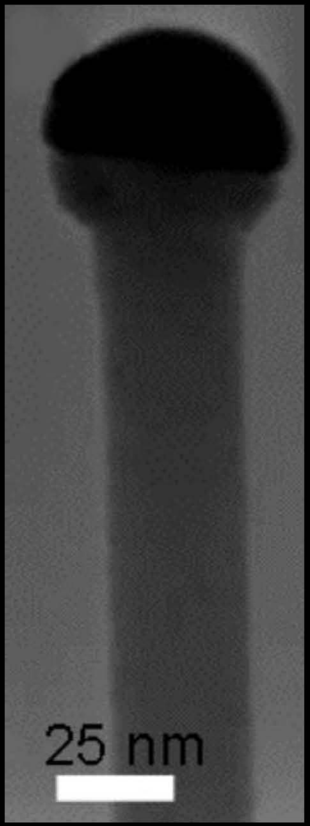




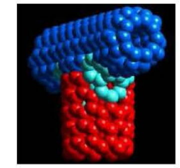
ZnO Nanowires



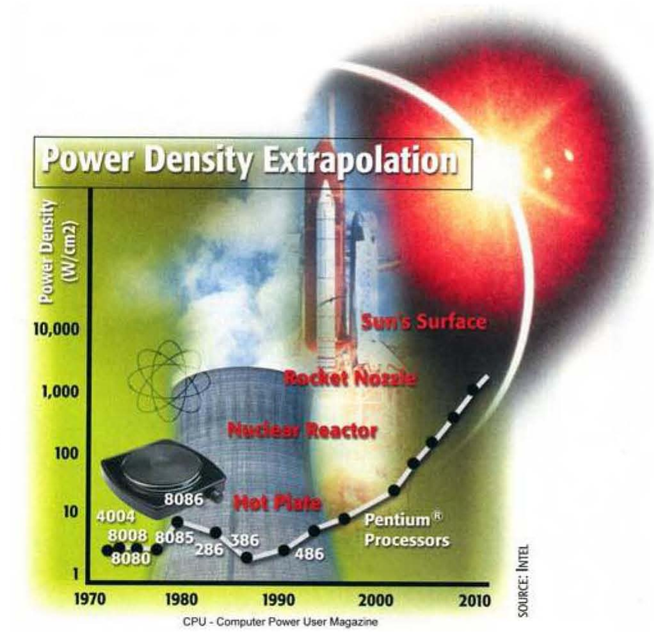
Germanium Nanowires

Nanoelectronics: What is Expected from Alternative Technologies?

(Beyond Silicon CMOS)



- Must be easier and cheaper to manufacture than CMOS
- High current drive; ability to drive capacitances of interconnects of any length
- High level of integration ($>10^{10}$ transistors/circuit)
- High reproducibility (better than ± 5%)
- Reliability (operating time > 10 years)
- Very low cost (< 1 μcent/transistor)
- Better heat dissipation characteristics and cooling solutions
- Novel architectures: Fault tolerant? Evolvable? Neural?
- Novel state variables: Spin?

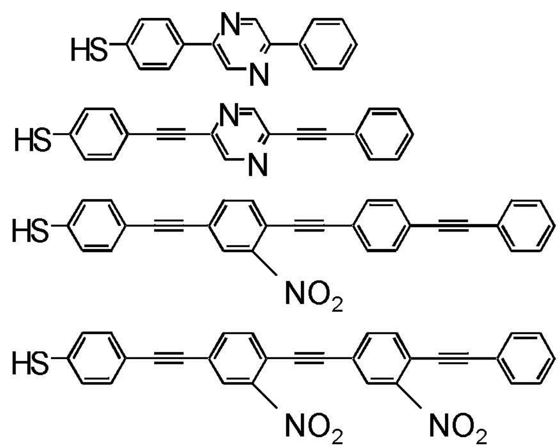


- Everything about the new technology must be compelling and simultaneously further CMOS scaling must become difficult and not cost-effective. Until these two happen together, the enormous infrastructure built around silicon will keep the silicon engine humming….

Nanoelectronics

Five possible avenues

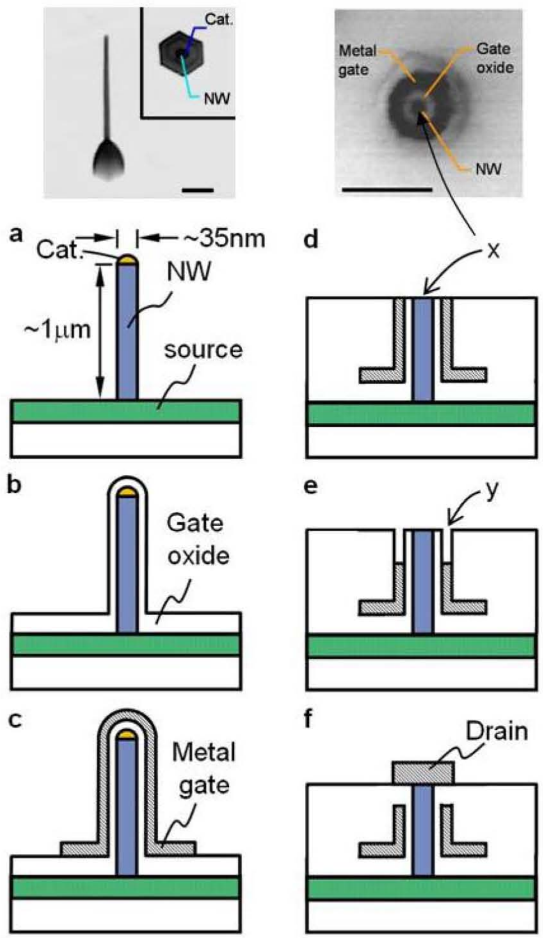
- Semiconducting single wall carbon nanotubes
- Graphene
- Nanowires (Si, GaAs, InP…)
- Organic Molecular wires
- Biomolecules (DNA)



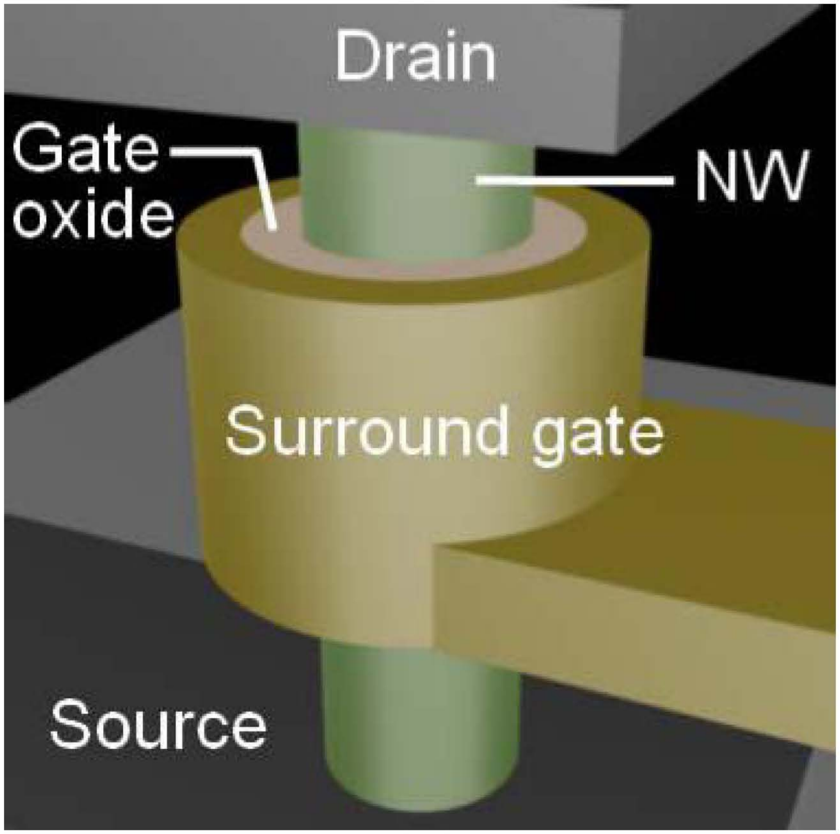
Examples of the SAM molecular materials to be used in the proposed work. SH is the substrate binding group, which will be chosen to form a strong bond to the Au substrate.

NASA Ames design, Wendy Fan

Vertical Surround-Gate Field Effect Transistor

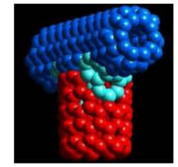


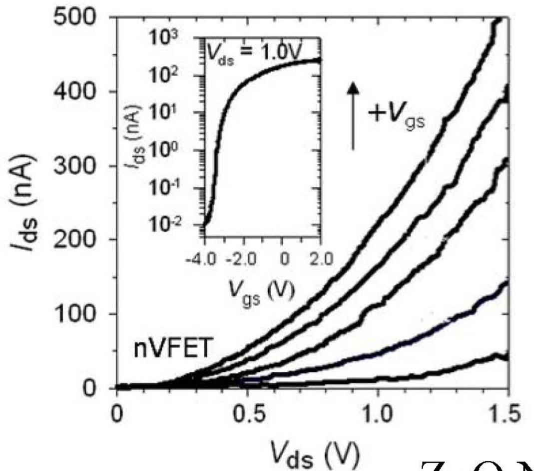
A process flow outlining the major fabrication steps of a VSG-FET.

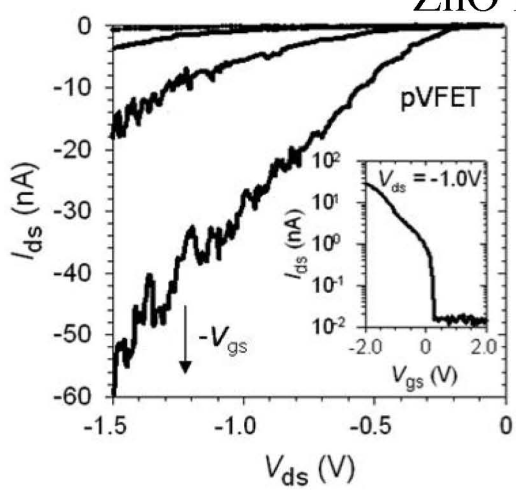


Ng *et al.*, Nano Letters, Vol. 4 (7), p. 1247 (2004)

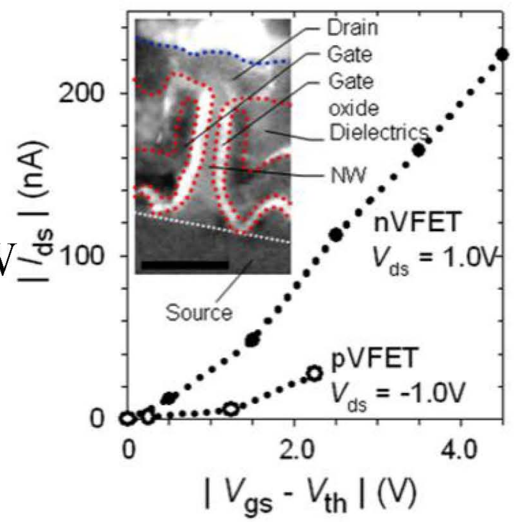
Vertical Surround-Gate Field Effect Transistor







ZnO NW

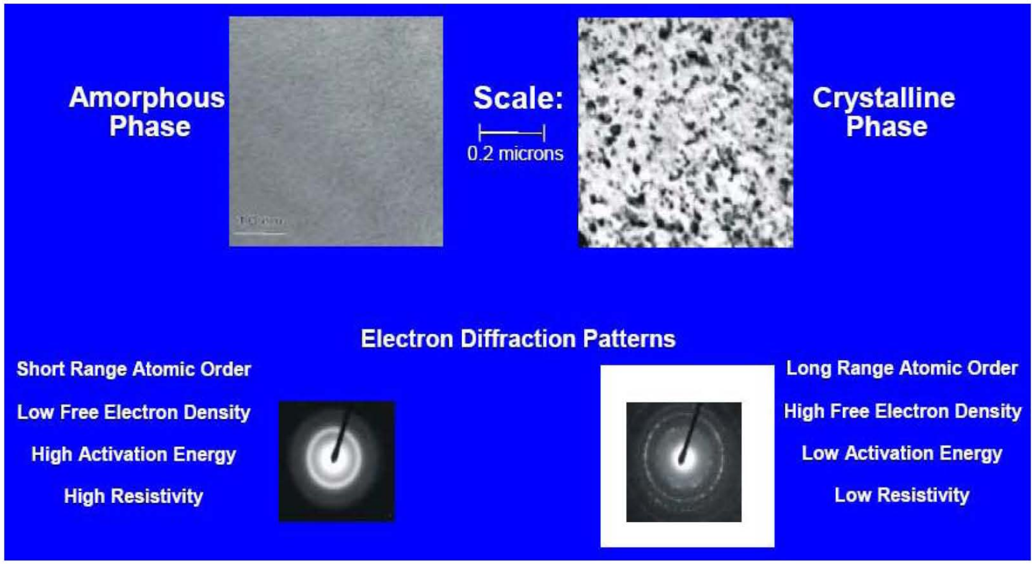


- In both n-type (normally on device) and p-type, $|I_{ds}|$ ⬆ with $|V_{ds}|$; threshold voltages - 3.5 V and 0.25 V respectively
- $I_{on}/I_{off} \sim 10^4, 10^3$; transconductance per nanowire 50 nS, 35 nS.

Ng *et al.*, Nano Letters, Vol. 4 (7), p. 1247 (2004)

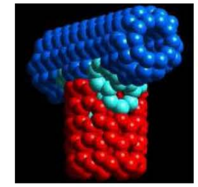
Phase Change Materials

- Phase change materials date back to 1960s
  - Mainstream optical storage media (CD-RW, DVD-RW)
- Common phase-change material candidates
  - GeTe, GeSbTe, In_2Se_3, InSb, SbTe, GaSb, InSbTe, GaSeTe, …



- Thermally induced phase change (orderly single crystalline or polycrystalline C-phase vs. less orderly amorphous α-phase)

Phase-Change Random Access Memory (PRAM)

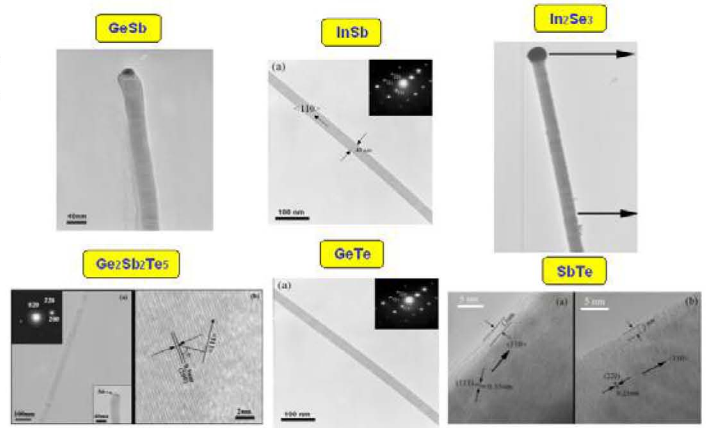


- Electrically operated phase-change Random Access Memory (PRAM)
  - Proposed nearly 3 decades ago
  - Binary or multiple resistive states of the programmable element to represent logic levels

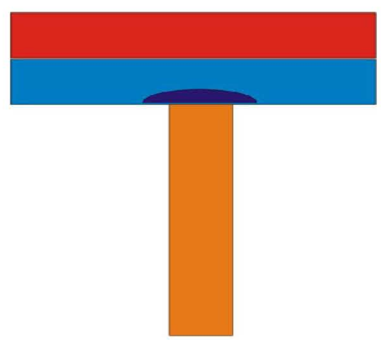
- PRAM advantages
  - Simpler fabrication than FET-based NVMs
  - Improved endurance (resistor-based)
  - Faster read/write
  - Binary or multiple resistive states
  - Soft-error or radiation free operation

Why 1-D Phase-Change Nanowire?

- Nanoscale Benefits
  - Smaller cell volume, leads to direct reduction of energy needs
  - Reduced melting point (30-50%)
  - Reduced thermal conductivity (1-2 orders of mag.)
  - Large aspect ratio (self-heating resistor)
  - Perfect surface morphology (not etched)

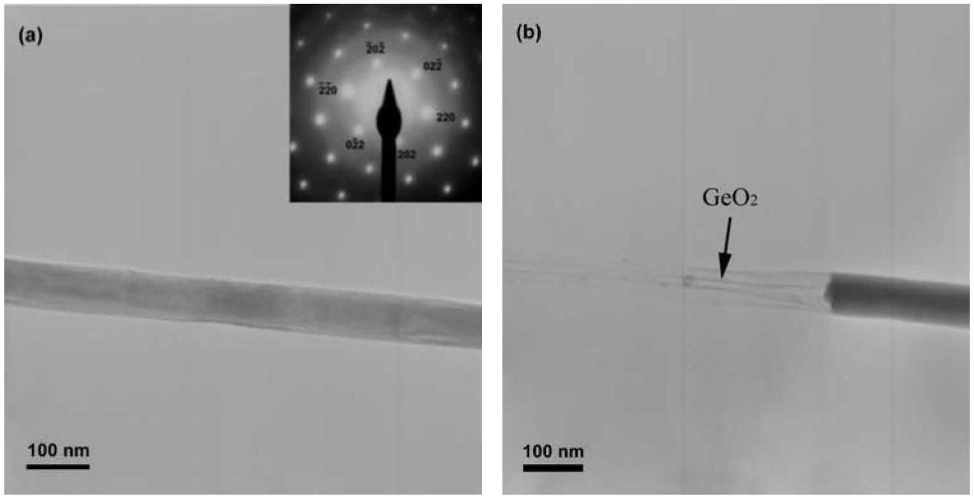


- Growth Benefits
  - Highly scalable critical size – diameter depends on catalyst size (down to ~ a few nm)
  - Etching-free
  - One-step LPCVD or MOCVD



2-D Thin film PRAM **1-D Nanowire PRAM**

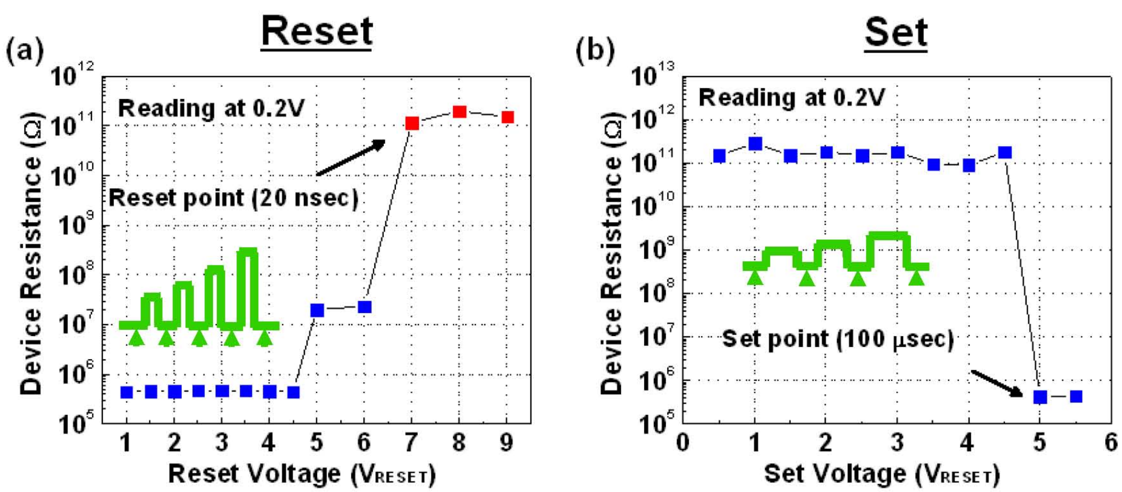
PCM Nanowires: Melting Point



	GeTe (d=70nm)	In_2Se_3 (d=40nm)
Bulk T_m	725°C	890°C
Nanowire T_m	390°C	680°C
Reduction	46%	24%

- The melting temperature of the phase-change nanowire is identified as the point at which (1) the electron diffraction pattern disappears and (2) the nanowire starts to evaporate.
- This property is diameter-dependent: reduction even more significant for smaller diameters

Indium Selenide NW Memory Switching



Storage Media	In_2Se_3 nanowire	In_2Se_3 Thin Film
Resistive Switching Ratio	**10^5**	**10^3**
Reset Current	**11 µA**	**0.4 mA**
Reset Power/Energy	**80 µW / 1.6 pJ**	**16 mW / 1.12 nJ**
Set Power/Energy	**0.25 nW / 25 fJ**	**14 µW / 140 pJ**
Reference	**Our Work**	**IEEE Trans. Mag. 41, 1034 (2005)**

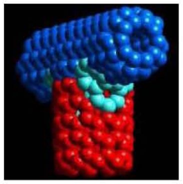
In_2Se_3 nanowire phase change memory switching behavior as a function of reset/set pulse voltage

Pulse width: (a) Reset at 20 nsec. (b) Set at 100 µsec.

Could be further reduced via memory size scaling

B. Yu et al., Appl. Phys. Lett. 91, 133119 (2007)

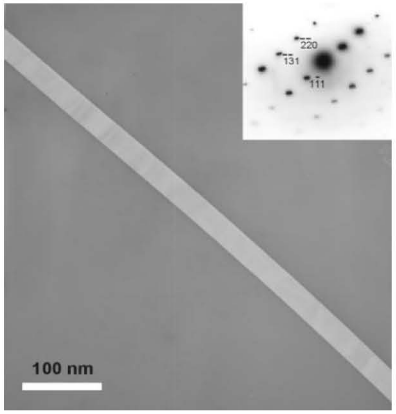
Highly-Scalable/Extremely Low Power/ Rad-Hard Data Storage



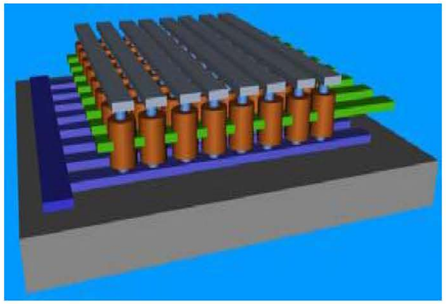
Next-generation non-volatile, resistive switching memory technology based on self-assembled phase-change low-dimensional nanomaterials

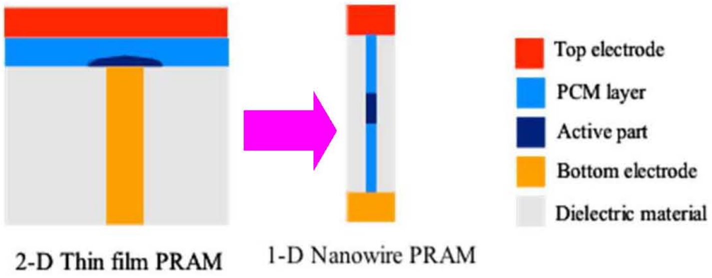
- 10^2~10^4 X lower Power Consumption
- 10~100X Memory Density
- 10~50 X Speed

Programmable 1-D Phase-Change Nanowires

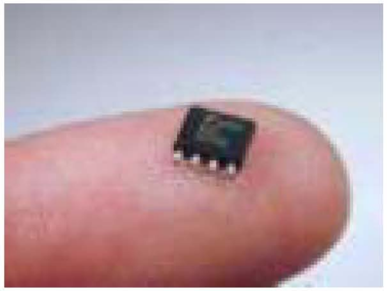


High-Scalable, Ultra-Low Power, Rad-Hard Memory Array





Superior Data Storage Performance Metrics

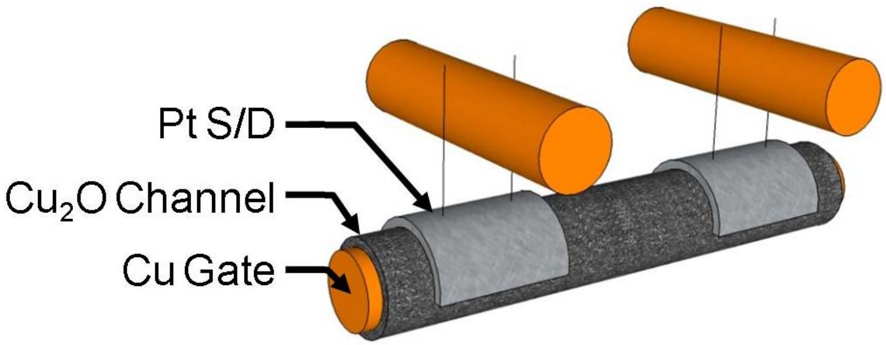


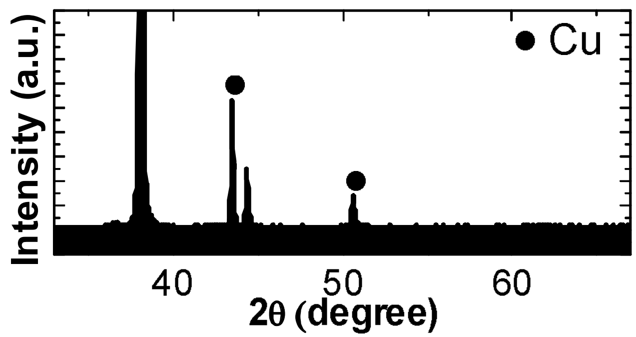
- Sub-1 V R/W operation
- 1 μA/cell reset current

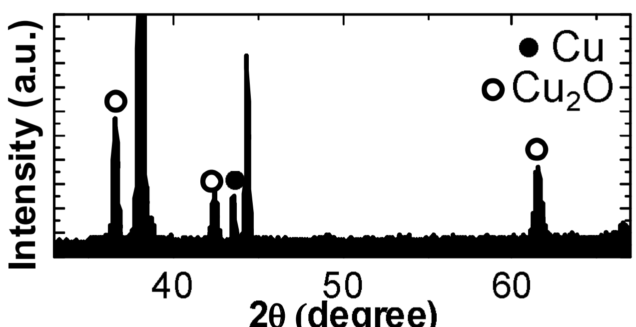
- 1~100 TB/cm^2 density
- < 10^{-12} J/bit switch energy

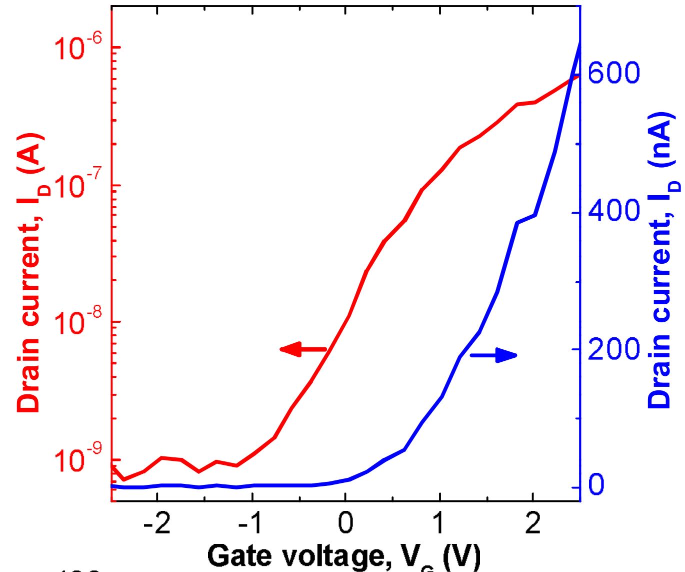
- < 10 ns write time
- > 10^{10} cycle endurance

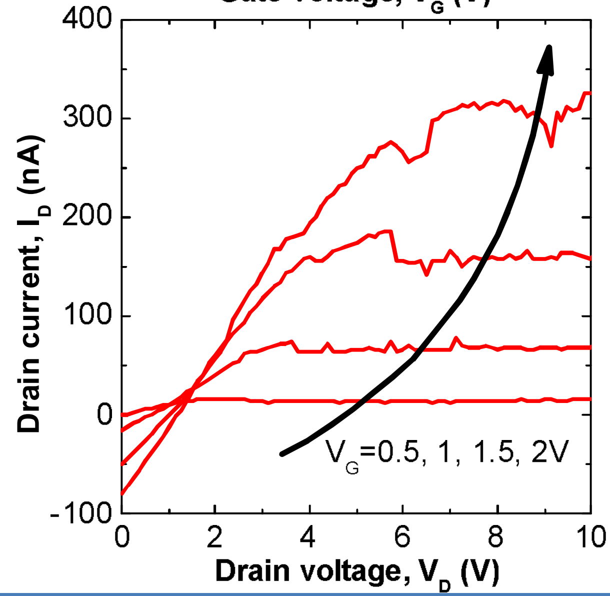
e-Textile with Transistor



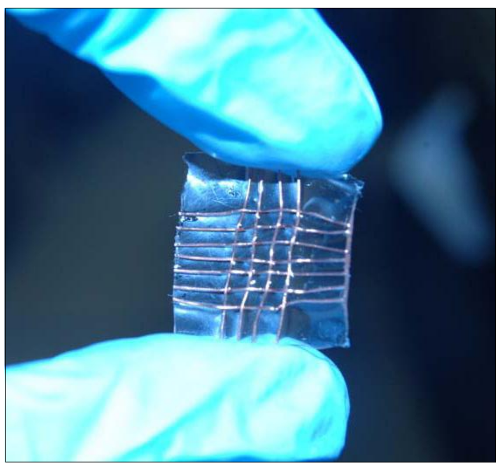


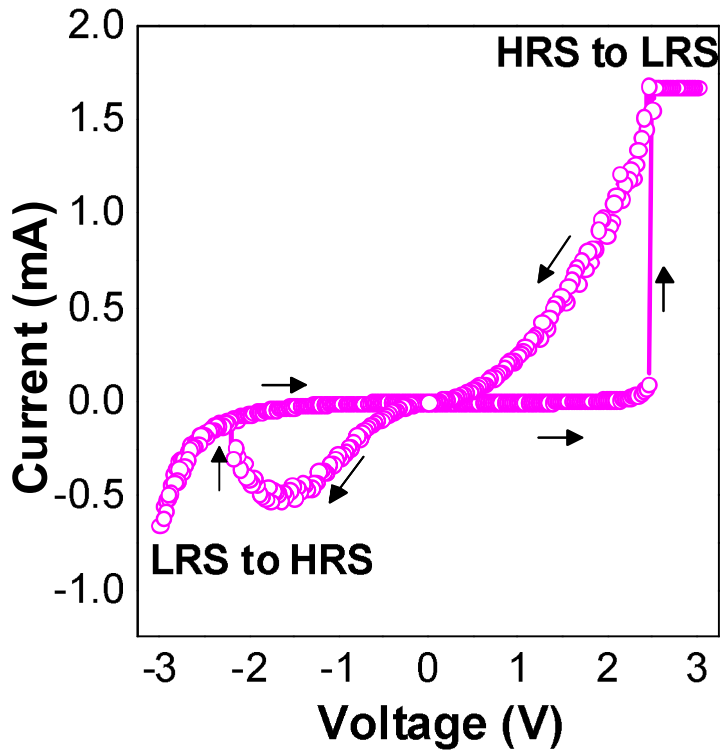




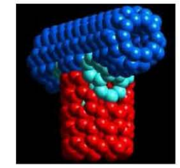


e-Textile with Resistive Memory





Optoelectronics Applications



- Devices
  - Photodetectors
  - Light emitting diodes (LEDs)
  - Nano lasers
  - photovoltaics

- Expected impact on:
  - optical switches
  - optical interconnects
  - optical waveguides
  - optoelectronic integrated circuits
  - electro-optic modulators
  - optical biosensors for lab-on-a-chip, biomedical, security needs

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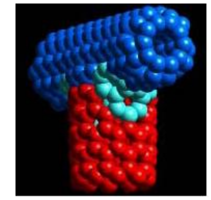
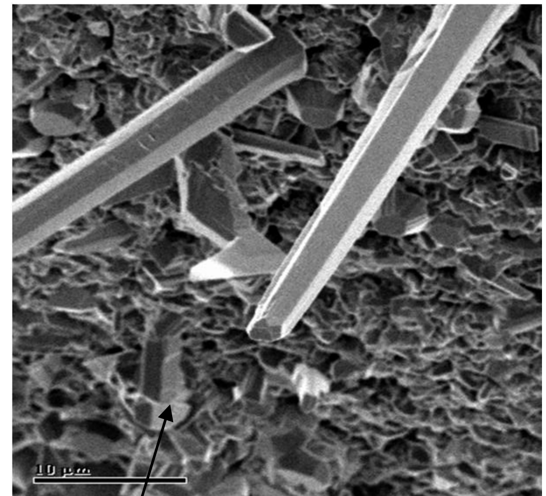
Nanoscale Lasers

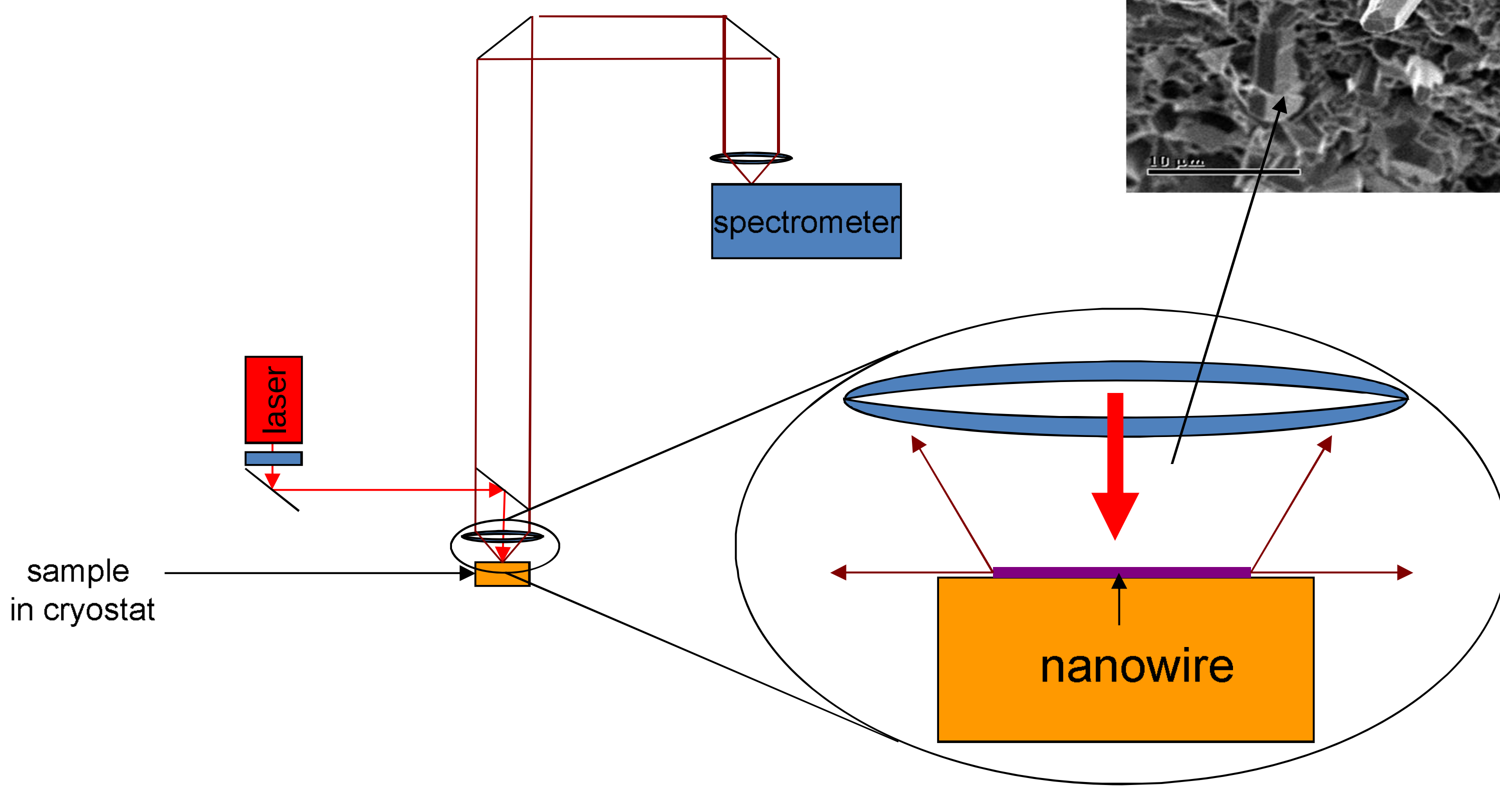
- NW diameter can be smaller than the emission wavelength in vacuum; length as long as several tens of µms; possibility of smallest lasers.
- Formation of optical cavity due to the difference in refractive index between the NW and surrounding.
  - larger this contrast → stronger the mode confinement
- Other advantages of NWs in lasers
  - cylindrical geometry
  - high quality crystal structure
  - vertical NW arrays for two-dimensional laser arrays
- Lasers investigated: ZnO, GaN, InN, ZnS, CdS, GaSb….

Infrared Photoluminescence Layout

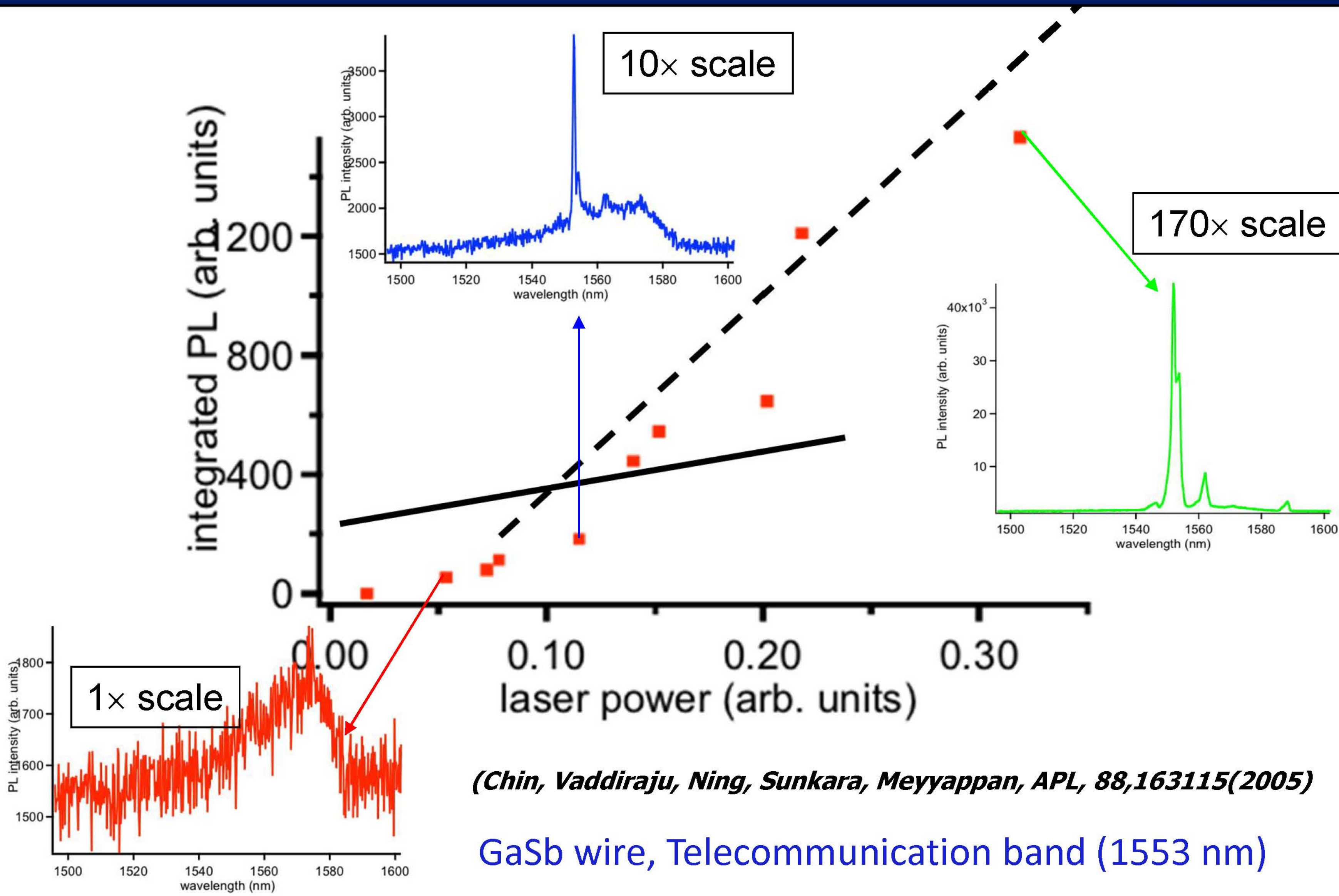


Pumping laser: Ti: sapphire mode-locked laser:
(800 nm, 150fs, 80 MHz Rep., 1.5 W average power)



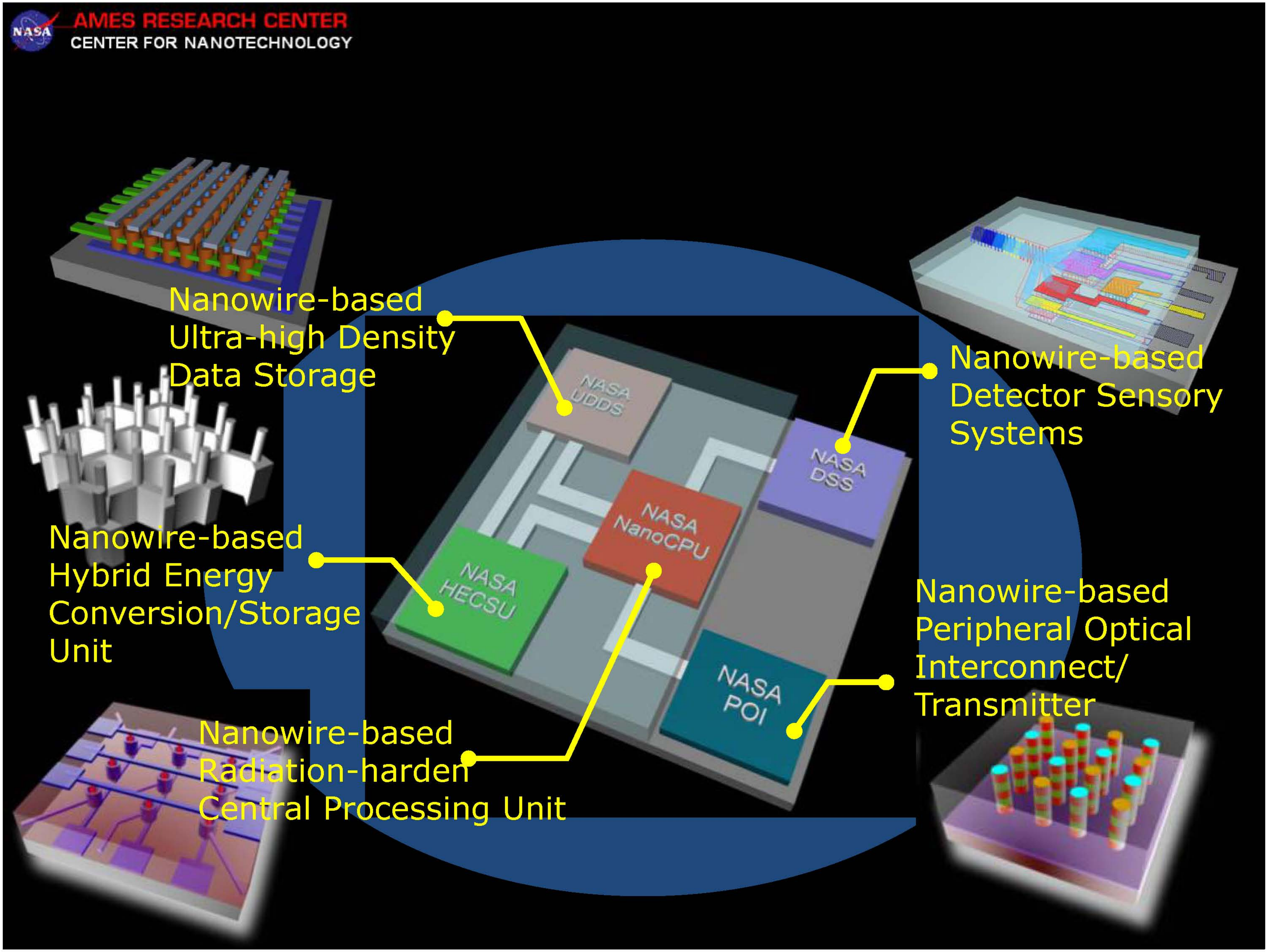


First IR Single NW Laser



(Chin, Vaddiraju, Ning, Sunkara, Meyyappan, APL, 88,163115(2005)

GaSb wire, Telecommunication band (1553 nm)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Nanowire-based Ultra-high Density Data Storage
Nanowire-based Detector Sensory Systems
Nanowire-based Hybrid Energy Conversion/Storage Unit
Nanowire-based Peripheral Optical Interconnect/ Transmitter
Nanowire-based Radiation-harden Central Processing Unit
NASA UDDS
NASA DSS
NASA NanoCPU
NASA HECSU
NASA POI